David Taylor Research Center

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Ship Materials Engineering Department

Research and Development Report

An Intelligent Control Strategy for the Spray Forming Process

by

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AN INTELLIGENT CONTROL STRATEGY FOR THE SPRAY FORMING PROCESS

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ABSTRACT

A control system incorporating a fuzzy logic inference engine and optical sensors has been developed for the spray forming facility at the David Taylor Research Center. An imaging system employing laser illumination and a high speed CCD camera provides critical on-line preform surface roughness and rate of growth information. A fuzzy logic controller utilizes a rule set to translate visual information into a form that can be reviewed by the conditional statements of the rule base. A high performance manipulator and motion controller have also been incorporated into the spray forming system. This discussion includes development of optical sensors and integration of advanced control systems to determine and activate required corrective actions to the spray forming process parameters.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The spray forming process is ideally suited for the application of intelligent control methods. The process has significant metallurgical and economic benefits, but requires more sophisticated control technology to achieve the level of reliability and reproducibility required for widespread commercialization. Currently, however, spray forming technology is limited to symmetrical shapes and requires trial runs to establish processing parameters. Development of in-process controls to minimize the trial and error method for establishing processing parameters would further reduce costs and make spray forming more commercially attractive. A program to implement real time sensing of preform temperature, rate of growth, and quality (as indicated by surface properties) has been undertaken at the David Taylor Research Center. The objective of the program is to develop sensor and control technology to monitor the critical process conditions and to modify parameters during the process to produce components with repeatable microstructural quality. This task has been divided into two phases, the first of which entailed development of sensors and controls to monitor and correct simulated process conditions. In the second phase, the selected sensors and controls are combined with actuators for integration with the DTRC equipment. Figure 1 is a diagram of the integrated sensing and control system as adapted to the spray forming process.

This program provides a cost-effective means to produce a variety of quality near net shaped products not now possible by spray forming. Such components can be substituted for higher priced forgings or lower performance castings. Additional benefits are in the form of improved domestic capability through technology transfer, the opportunity to produce shapes and material combinations not currently feasible, the opportunity to develop improved performance/lower cost components for military applications at an accelerated rate, and advanced sensors for potential use in other metals processing applications.

BACKGROUND

In the spray deposition process, a stream of molten metal is atomized by an inert gas, producing a spray of liquid droplets which are cooled by the gas and accelerated towards a substrate, where they consolidate to form a fully dense deposit. The process improves on ingot metallurgy in that a rapidly solidified, grain-refined microstructure with limited segregation is produced. Spray forming exhibits the beneficial characteristics of powder metallurgy processing without the numerous stages involved, such as powder production, storage and handling, sintering and hot consolidation. A program at the David Taylor Research Center sponsored by the Office of Naval Technology evaluated the feasibility of utilizing (Osprey) spray forming to produce Alloy 625 (Ni-Cr-Fe-Mo) piping. The results of this program showed that fully dense preforms could be sprayed and roll extruded into piping with properties equivalent to conventionally made piping at substantially reduced costs[1]. Cost savings projections for simple shapes such as piping tubulars produced via spray forming are as high as 30 - 50% versus conventional processing technology. The technology is alloy non-specific and therefore is applicable to a wide range of metallic systems.

OBJECTIVE

The objective of this program is to develop real time sensor and control strategies for the spray forming facility at the David Taylor Research Center. Adaptive control techniques utilizing process parameter data as inputs from sensors will insure process reproducibility and preform quality. In addition, this program is aimed at expansion of current motion capablities to include nonsymmetric parts.

PROCESS CONTROL STRATEGY

The purpose of intelligent control is to establish relationships or mappings between the locally controlled, primary process parameters and indicators of final part quality which can be sensed and controlled in real time[2]. These mappings may be represented by mathematical models, expert systems, neural networks or other forms of knowledge representation. In some cases, more than one type of control method may be employed[3]. In the case of spray forming it is known that expert operators typically observe the preform during spraying, and that surface roughness and rate of growth are two measurable quantities related to final preform quality. Operators modify the primary process parameters in response to visually observed changes in the secondary or dependent parameters, surface roughness and rate of growth. These dependent parameters can be sensed in real time using advanced techniques. Fuzzy logic control was selected for the control strategy as it provides a way of representing inexact process knowledge as well as resolving conflicts in sensor and control data through the use of fuzzy set theory.

Spray forming process parameters such as melt superheat, primary and secondary atomizing gas pressures, flight distance and preform withdrawal rate affect each of the spray forming subprocesses (atomization, consolidation and solidification) in ways which can be understood qualitatively in terms of well defined metallurgical phenomena. While mathematical models are now being developed for the spray forming process (and subprocesses), these remain too complex for application to real time control[4,5]. However, a qualitative understanding of the mechanisms operating in each subprocess can be embedded in rules relating various primary process parameters to sensor data and desired part properties. Fuzzy methods are well suited to metallurgical processes, many of which, like spray forming, are actually multiple coupled subprocesses, and in which it may be difficult to resolve information from the multiple sensors required for monitoring[6,7].

The Fuzzy Logic Controller (FLC) assesses the status of each run during processing and output control values to help correct for various anomalies that are inherent to the spray forming process. The FLC accomplishes this by executing fuzzy subset theory logic operations contained in an operator selected rule set. The inputs and outputs to the Fuzzy Logic Controller are based on critical, definable process parameters that can be quantified. Inputs include surface roughness, rate of deposition, surface temperature, metal flow rate, secondary gas pressure and motion profile variations. Every cycle, the FLC reads in control inputs from a run manager database. The rate at which the FLC operates is approximately 10 hertz. Once the control inputs have been read in, the FLC goes through each rule contained in the system. Rules are in the form of IF - THEN conditional statements. For each rule, the FLC will perform the corresponding fuzzy logic to determine a value that can be related to a desired output, and rules can be thought of as being grouped according to the outputs they affect. The fuzzy logic controller provides a means of analyzing sensor data and making variable process corrections in much the same way that a skilled operator might, while the protocols of fuzzy set theory and membership functions permits dealing implicitly with transient phenomena and conflicting data.

SENSORS

Sensing the basic process parameters such as melt temperature, atomizing gas pressure, metal flow rate and withdrawal rate can be accomplished with conventional, commercially available sensors. Quantifying preform surface roughness and rate of growth in real time, however, has proven to be a challenging sensor task. All sensing methods that require contact with the preform are precluded by the semi-liquid state of the preform. Sonic and ultrasonic sensors are highly unstable in the dynamic thermal environment of the spray forming chamber. As a result, an optical sensor has been selected.

A single optical sensor has been developed that simultaneously measures rate of growth and preform surface roughness. Emphasis to date has been placed on laser striping techniques which provide preform surface roughness measurements and can be correlated to preform quality in terms of porosity. The method for surface roughness determination is described in detail below.

The sensing system consists of a laser, a CCD video camera, acquisistion and enhancement software, roughness determination software and an error accommodation provision. The laser stripe is projected onto the surface of the depositing preform which is viewed with a video camera placed at an angle to the laser-preform line. This allows the camera to acquire an image of the surface profile.

The laser wavelength was selected so that band-pass filtering could be implemented to attenuate the thermally induced radiation of the preform. Also the selected wavelength must fall within the CCD camera sensitivity range. As a result of the above criteria, an argon laser producing a single wavelength (514 nm) of light was chosen. The optimum power level was determined experimentally to be 10 mW.

The surface profile image is acquired by the CCD camera using a 0.01 sec shutter speed. A commercially available frame grabber is utilized to conduct the image enhancement. The image of the projected laser stripe is first enhanced by optical filtering, then a 3x3 convolution is executed on the image. Thresholding is executed to eliminate any background noise. The resulting image is analyzed, line by line, to find the location of the laser stripe using a center of gravity calculation. The output of this analysis is a profile of the preform surface as it varies with time during the spray forming run.

The profile is high-pass filtered with an infinite impulse response (IIR) digital filter and the root mean square (RMS) value of the filtered waveform is calculated. The RMS value is then forwarded to the Fuzzy Logic Controller. The rate of change of the D.C. offset of the unfiltered data correlates to a deviation from the planned rate of growth of the preform. The profile of the preform is determined by polynomial fitting using a least-means-square criterion.

To detect and accommodate errors, after each frame is acquired, the system checks the image to determine if thresholding can be executed properly by comparing peak values to average intensity values. If peak values are not sufficiently higher than the average values, the frame is discarded and another acquired. If during line-by-line analysis, no values are found greater than the threshold value, then that line of the preform profile is disregarded, but the rest of the information in the frame is kept.

MOTION CONTROL

Enhanced manipulation capability is critical to the application of intelligent control to spray forming. Droplet flight distance strongly affects the temperature and liquid fraction of the material deposited at the preform surface, which is in turn a primary factor involved in preform microstructure, macrostructure and density. In order to fabricate complex shapes it must be possible to vary ram position rapidly in order to maintain a constant flight distance.

A high performance manipulator and flexible motion controller are required to produce asymmetric shapes and to enable droplet flight distance to act as a control variable. The manipulator has five axes of motion including x, z, wrist roll, wrist pitch and tool roll with an optional y axis that can be added as required. Some of the shapes to be spray formed include elbows, nozzles and hemispheres in addition to the pipe, billet and plate that can be spray formed using existing technology. Parts weighing up to 68 kg and measuring up to 61 cm in length can be accommodated. The motion and acceleration requirements for these shapes have driven the manipulator design. In addition, the motion controller and manipulator permit modifications during runs based on the fuzzy logic controller inputs.

The axes of motion are controlled by a multi-variable control scheme, required by the cross-coupling between the three revolute joints, which operates at up to 500 Hz. Inputs to the motion controller include motion profiles created off-line as part of the planning process, motion profile corrections output by the fuzzy logic controller, profiles for the gains in the multi-variable controller and multi-variable gain profile corrections output by the fuzzy logic controller. In response, the outputs from the motion controller are manipulator position commands to the hydraulic motors and manipulator position feedback to the run database.

Initially, motion profiles are developed as a planning and simulation activity and represent a best guess estimation of the optimal approach. Based on sensor data about part quality, these profiles can be corrected during an actual run. As kilograms of metal are added to the manipulator, the dynamics of the mechanical system change significantly over the course of a run. The gains of the motion controller change as a result. These changes are input as gain profiles during planning and can be modified by the fuzzy logic controller. This combination of mechanical performance, high update rate and control flexibility enables the manipulator to support the requirements for spraying asymmetric shapes.

CONCLUSION

A program to develop sensor and control technology for real time implementation with spray forming has been undertaken at the David Taylor Research Center. The objective of this effort is to insure reproducibility and quality of spray formed products and to expand the capability to manufacture asymmetric shapes. Sensor data is used by a fuzzy logic intelligent controller to make adjustments to spray forming process parameters during preform deposition. Advanced manipulation capabilities are required to produce asymmetric components.

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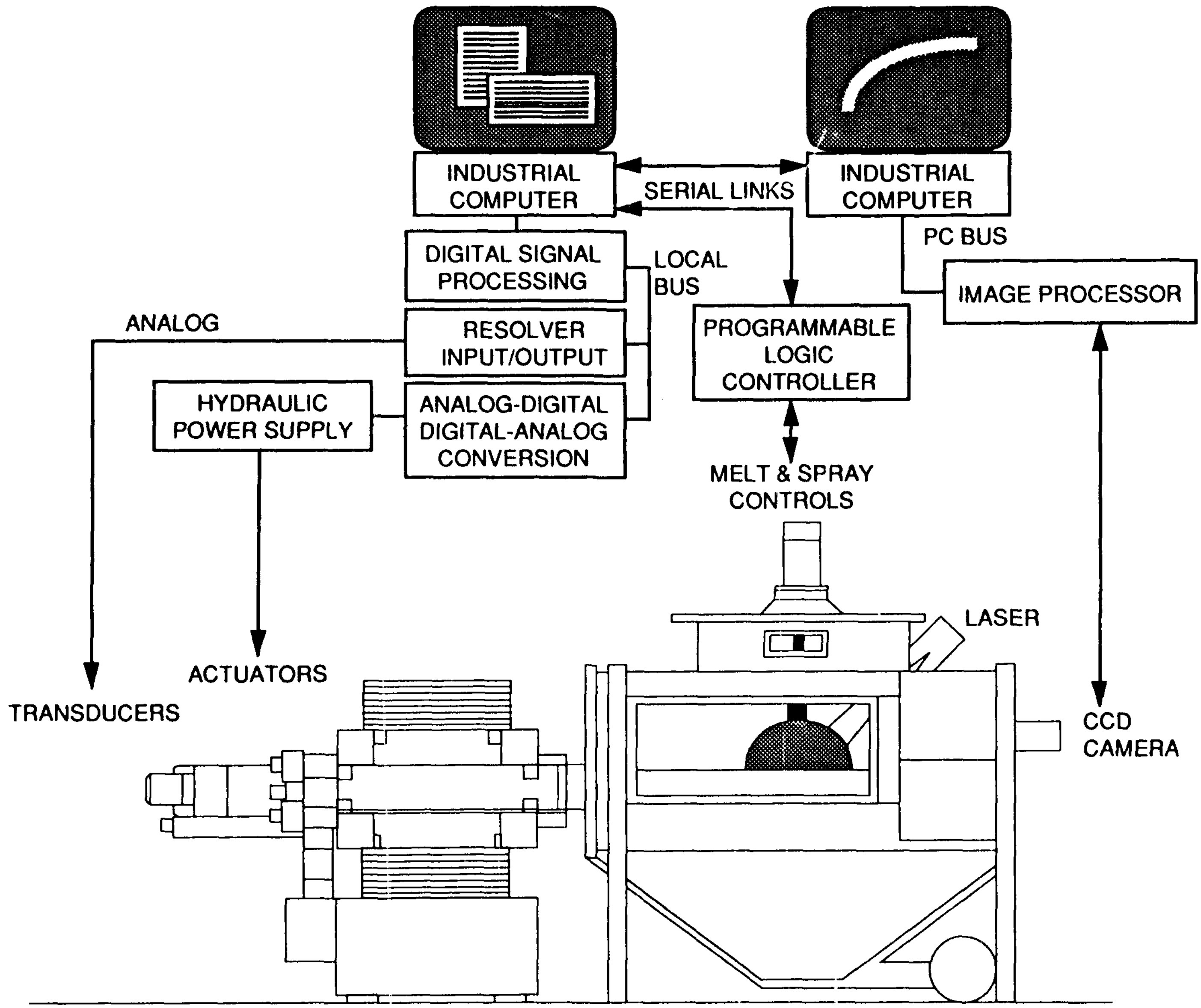

Figure 1. Integrated Sensing and Control System.

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